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Fertilizer Research and Education Program (FREP)
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Sacramento, CA 95814**

Final Report for Project Ending 5/31/99

Prepared by Blake Sanden, November 10, 1999

**Project Title: Effects of irrigation nonuniformity on nitrogen and water
 use efficiencies in shallow-rooted vegetable cropping
 systems**

Contract Number: 95-0519

Project Leaders:

Jeff Mitchell University of California Cooperative Extension Vegetable Crops
 Specialist
 Vegetable Crop Production and Post-Harvest Physiology
 Kearney Agricultural Center
 9240 S Riverbend Ave.
 Parlier, CA 93648

Laosheng Wu University of California Cooperative Extension Specialist & Assistant Professor
 Soil Physics, Water and Nutrient Transport/Modeling
 University of California Riverside
 Department of Soils and Environmental Sciences
 Riverside, CA 92521-0424

Blake Sanden University of California Cooperative Extension Farm Advisor, Kern County
 Irrigation Management and Agronomy
 1031 S. Mt. Vernon Ave.
 Bakersfield, CA 93307

Objectives:

Evaluate the effectiveness of standard and alternative sprinkler lateral spacing in solid-set sprinkler irrigation systems on water and N fertilizer use efficiencies in commercial carrot production systems in the Southern SJV by:

- 1) Characterizing in-field irrigation distribution uniformities and their relation to soil N distribution and leaching and the impact on crop N distribution, yield, and quality.
- 2) Adapt an existing computer model to assess water and N fertilizer management under various sprinkler lateral spacings.
- 3) Determine the impact of sprinkler age on DU. (Added for the 1998-99 season.)

Executive Summary:

Seven different sprinkler lateral spacings of 33.3 to 48 feet over three different carrot plantings were tested. The same field was used for the Spring 1996 and Fall 1997 trials with subsampling from nearly identical locations for both years. The age of sprinklers used each season were: new (Spring 1996), two years old (Spring 1997), and greater than three years old (Fall 1997). The first trial was planted on 40" beds with the last two on 36" beds.

In-field Irrigation System Distribution Uniformity (DU) as measured with periodic catchcan evaluations varied from a mean low of 71.8% for a 45' spacing with the 3+ year old sprinklers to a high of 86.0% for the 46.7' spacing with new sprinklers. The 40' and 42' spacings were the most consistent regardless of age at 77.4 to 82.0%. All of these values exceed the 65 to 70% mean DU reported for most hand-move solid-set aluminum pipe in California. The age of sprinklers and nozzles made the biggest difference; with a mean evaluation DU of 81.6, 79.1, and 74.8% for the new, two year, and 3+ year old sprinklers, respectively. Leaching and applied water is always greatest near sprinklers when nozzles and spoons are more than two years old.

A "mean normalized sprinkler DU" was calculated to estimate the uniformity of precipitation for the whole season. This value accounts for shifts in wind pattern from one sprinkler evaluation to another and provides a more "plant based" viewpoint of seasonal precipitation uniformity. The result is a general increase of 4 to 8% in seasonal DU over the straight mean DU. These DU's (from a low of 81.6 to a high of 90.8%) are more consistent with the uniformity of total root system yield as discussed below. Natural rainfall greatly increased the seasonal uniformity of the Fall 1997 trial. (See Table 1 and Figures 2 through 5.)

Total root yield and quality was not statistically different for any of the spacings for sampling over the entire field, although a consistent trend of 2 to 6% increased yield for the closest spacing was observed for each trial. Total root yield for the 42' foot intensively monitored grid in the Spring 1997 trial was significantly greater than the grid from the 48' spacing by 6.2 ton/ac (Table 1), but this difference was reduced to 1.5 ton/ac for overall field sampling. Total root yield DU ranged from 81.5 to 89.3% with no significant differences from lateral spacing. Total precipitation in monitored grids ranged from 75 to 160% of ET for the season depending on location relative to sprinklers. There was no correlation with yield and applied water at these

levels (Fig. 6) for any spacing, suggesting that carrots are capable of maximum yield even under some deficit irrigation.

Nitrate leaching as estimated by anion-exchange resin bags was not related to lateral spacing. It was found to be 7 to 12% (19.2 to 30.5 lb/ac) of applied N in the Spring 1996 trial. The 40.0' lateral spacing leached significantly less nitrate than the 33.3' or 46.7' spacings even though the 46.7' spacing proved to have the highest mean DU. An 85% efficiency of nitrate recovery was established for these bags using soil columns prepared from soils used in these trials. Use of these resin bags to accumulate total leached nitrate seemed highly promising after the first season. Intercepted nitrate in the Spring 1997 trial jumped to 18 to 27% of applied N. Resin bag results from the Fall 1997 trials, however, showed impossibly high levels of intercepted nitrate of 66 to 132% (in excess of 300 lb/ac $\text{NO}_3\text{-N}$). $\text{NO}_3\text{-N}$ concentrations in soil solution access tubes (SSAT) were also unrealistically high. Further confounding these results is the fact that intercepted resin bag nitrate decreased as leaching of irrigation water increased. This is not supposed to happen. Appropriate lab procedures appear to have been followed and control bags showed zero-nitrate contamination. Residual soil nitrate concentrations dropped as depth of applied water increased. Resin bag nitrate accumulations were significantly related with soil nitrate levels at the 2 to 3' and 3 to 4' depths ($R^2 = 0.37$ and 0.47 , respectively).

Computer modeling simulations (adapted from the ENVIRO-GRO model developed by Pang and Letey (1998)) using a Monte Carlo approach to vary soil hydraulic properties, calculated the average ET, percolation, N uptake, nitrate leaching, and relative yield for carrots. These simulations have revealed that even modest heterogeneity of the soil hydraulic characteristics becomes more important than the irrigation system DU. Using simulated DU's of 50, 75, 90 and 100%, total nitrate leaching had no significant correlation to lateral spacing for carrots with a 2 1/2 to 3' root system for a finer textured soil like a silty clay loam. In contrast to our field results, however, we found that simulated leaching decreased and relative yield increased on a course sandy loam, such as the soils encountered in this study, as DU increased. This correlation may become even more significant for shallower-rooted vegetable crops that were not tested with in this trial, but still does not account for the higher seasonal DU that can occur in the field.

Regional irrigation system evaluations to examine the impact of sprinkler age revealed that this factor was not significant in improving DU. Forty-two evaluations of solid-set systems (carried out between June 1998 and May 1999) ranging in age from 1 to 10 years in ten different fields compared the grower's sprinklers, as found, with new nozzles and new sprinklers. Increasing system age showed a slight trend toward decreasing uniformity, but direct comparison of the original sprinklers, new nozzles and new sprinklers showed no impact at all for age for a given system. Set duration, or cumulative precipitation, made the most significant impact on DU. A very clear breakpoint at 10 hours was evident. Below this duration DU averaged around 72%. At or above this threshold the average was about 78%.

Finally, despite the results of 44 separate evaluations of the seven different lateral spacings examined during the carrot trials, narrower lateral spacing in these regional evaluations gave significantly higher DU than the 45 to 48 foot spacings (Figure 15). This also concurs with our computer modeling simulations in which DU improved with narrower spacing. Our earlier field work in this project, however, indicates that this benefit may disappear when considering precipitation uniformity over the whole season, and probably not translate into any yield benefit for carrots even though computer simulations on sandy soil say that yield should be improved.

DESCRIPTION

Task 1: Characterize in-field irrigation distribution uniformities and their relation to soil N distribution and leaching and the impact on crop N distribution, yield, and quality to corroborate first and second year findings.

Subtask 1.1: Three different carrot plantings using seven different sprinkler lateral spacings of 33.3 to 48 feet have been monitored in the Rosedale area of western Kern County in cooperation with Bolthouse Farms. The age of sprinklers used each season were new (spring 1996), two years old (spring 1997), and greater than three years old (fall 1997/winter 1998). The first trial was planted on 40" beds with the last two on 36" beds. Irrigation duration was scheduled in an attempt to apply the same depth of water (about 2" for established carrots) to all spacings. For summer 1998 through spring 1999 this task was adapted to test for the impact of sprinkler age on DU in grower fields.

Subtask 1.2: Intensive soil sampling for baseline characterization of soil physical and chemical characteristics was done for the field used in the Spring 1996 and Fall 1997 trials. These data were used for field evaluation and computer modeling calibration.

Subtask 1.3: Multiple irrigation evaluations for sprinkler distribution uniformity (DU) were done periodically throughout the season using 30 to 48 catchcans depending on spacing.

Subtask 1.4: Crop growth, canopy development, roots and tops biomass, and N content were measured up to eight times during the season.

Subtask 1.5: Field water content determined by neutron backscatter was used to monitor all plots to optimize irrigation scheduling performed by Bolthouse, determine crop ET, and estimate leaching. Anion exchange resin bags were also placed at these locations at a depth of 3' and changed two to three times to estimate total nitrate leaching. In addition to these grids, four replicated sites measuring yield, soil water content, precipitation, and nitrate leaching were established at 3 to 4 locations in each lateral spacing (Fig. 1) in an attempt to sample the spots of high (Middle), medium (Mid Sprink), and low (Lateral) precipitation. Anion exchange resin bags (25 sq.cm. with 5 dry grams of BIO-RAD AG 1-X8 resin) were installed at 3' and retrieved three times during the season to monitor nitrate leaching. Soil solution access tubes (SSAT) were installed in the final two trials as a spot comparison with resin bags. These monitoring sites corresponded to soil sampling locations where samples were collected at four depths (0-1', 1-2', 2-3', 3-4') at planting and at harvest.

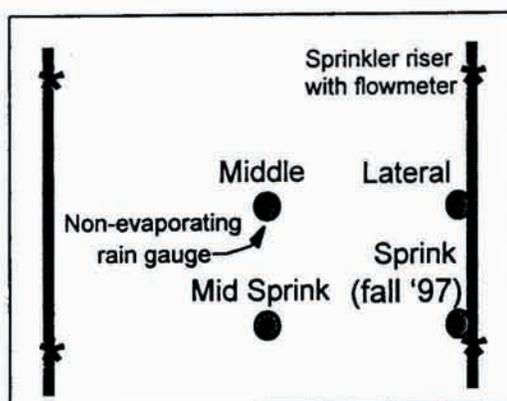


Figure 1. Key to replicated monitoring sites.

Subtask 1.6: Spatial patterns of carrot yield and quality were determined by digging a 5' long section of one half of one bed in each of the cells in the intensively monitored grids corresponding to soil samples described in Subtask 1.3. Field

wide yield was determined by samples harvested in the same manner at the replicated locations as shown by Figure 1. These locations are the same as those for Subtask 1.5.

Subtask 1.7: Data summary and analysis was accomplished with a variety of techniques. Sprinkler precipitation distribution has been graphically illustrated with surface maps and spatial patterns of precipitation and soil nitrate distribution have been described using semi-variograms to search for spatial dependency. Means separation were tested using Fisher's Least Significant Difference. Computer modeling validation was completed using loamy sand, sandy loam and silty clay loam soils.

Subtask 1.8: A cost/benefit analysis of narrower sprinkler lateral spacing over conventional spacing has not been carried out at this time. As our study showed no benefit of decreasing lateral spacing in our moderate wind conditions in the San Joaquin Valley, an economic analysis seems rather pointless. Likewise a grower publication advocating narrower spacing is not warranted. A possible publication would basically consist of general sprinkler management practices. Such publications already exist.

Field Site Descriptions

1996 Field Trial: In the west 60 acres of a 100 acre carrot field planted on 40" beds planted 1/29/96 and harvested 6/4/96, solid-set sprinkler laterals (with sprinklers every 30' along the lateral) were set up in groups of four laterals spaced at 10 beds (33.3'), 12 beds (40.0'), and 14 beds (46.7'). Each of these three spacings were randomized within a block and replicated three times across the field. Duration of irrigation sets was adjusted for lateral spacing to apply 2.4 gross inches (a 2.0" net @ 80% DU) of precipitation per set. All irrigation pipe and sprinklers were new with nozzle pressures of 52 to 56 psi. Rainfall was negligible.

Nitrogen fertilizer as a 7-10-41 liquid mix was applied at 120 lb/ac-N preplant and an additional 130 lb/ac applied through the sprinklers during the season as UAN-32.

One intensively sampled grid with each node consisting of 2 beds wide by 5' long was established between sprinklers in each of the spacings. This required 30 to 42 sample points depending on lateral spacing. In addition to these grids, five replicated sites measuring yield, soil water content (weekly, using the neutron probe), precipitation (using non-evaporating rain gauges), and nitrate leaching were established at 3 locations in each lateral spacing in an attempt to sample the spots of high, medium, and low precipitation. Anion exchange resin bags (25 sq.cm. with 5 dry grams of BIO-RAD AG 1-X8 resin) were installed at 3' and retrieved three times during the season to monitor nitrate leaching.

1997 Field Trials:

Spring 1997: A 32 acre demonstration field planted to carrots on 36" beds planted 3/16/97 and harvested 6/27/97 was set up with one set of 20 laterals spaced at 42' and the second set spaced at 48' (the production spacing used for the entire field). Pipe and sprinklers were about two years old. Pressures were occasionally excessive (62 to 70 psi). Rainfall was negligible.

Replicated monitoring was done as listed above for each set (3 reps for each spacing) but spacings were not replicated in blocks across the field. Resin bags were changed only two times.

Fall 1997: The same field and experimental design as in 1996 was used with planting on 9/1/97 and harvest on 2/10/98. Beds were 36" wide this time with tested spacings being 36' (the new standard for Bolthouse), 42' and 45'. However, sprinklers and nozzles were more than 3 years old. Excessive nozzle and gasket wear caused booster pressure to be insufficient to drive the same number of sprinkler lines as in the first trial. This required switching the third block of monitoring sites from its original location on the west side of the field to the south side of the field opposite Block 1. This did not affect the siting of the intensively monitored grids that corresponded to the first trial and still provided for three replicated blocks.

Due to observing more 'overspray' near the sprinkler for the Spring 1997 trial when using older sprinklers, we decided to add a fourth monitoring location near the sprinkler for each plot. (See key to monitoring site locations for Tables 4 and 6.) Pressures for the 36' spacing were often excessive as a new oil well development replaced some of the planted acreage that was set to the 36' spacing; reducing the number of sprinklers compared to the other spacings. This field was grown for cello (long) pack carrots and not the short cuts as in the other two trials. This requires a longer growing season. This field also received 5.19" of rainfall during December and January.

June 1998 and May 1999: Regional irrigation system evaluations to examine the impact of sprinkler age. Forty-two evaluations of solid-set systems in ten different fields throughout Kern County on irrigation systems ranging in age from 1 to 10 years were carried out between. Set duration ranged from 4 to 12 hours. The grower's existing system DU was evaluated in the same manner as for the carrot fields in the earlier part of this project. Using the same two laterals as those for the grower's system evaluation we installed a second set of catchcans four joints of pipe down the line (120 feet) and a third set another four joints down from that (240 feet away from the first catchcan set. For the 12 sprinkler heads surrounding the location of the second catchcan set we installed new nozzles (either 7/64 or 1/8 inch depending on the grower's system) into the grower's old sprinklers. For the third set, 12 new sprinkler heads were installed. The old sprinkler, new nozzle and new sprinklers were of course run simultaneously so that wind conditions and duration would be identical for all three evaluations.

Results and Discussion

Irrigation System Distribution Uniformity (DU) as measured with periodic catchcan evaluations varied from a mean low of 71.8% for a 45' spacing with the 3+ year old sprinklers to a high of 86.0% for the 46.7' spacing with new sprinklers. The 40' and 42' spacings were the most consistent regardless of age at 77.4 to 82.0%. All of these values exceed the 65 to 70% mean DU reported for most hand-move solid-set aluminum pipe in California. The age of sprinklers and nozzles appeared to make the biggest difference; with a mean evaluation DU of 81.6, 79.1, and 74.8% for the new, two year, and 3+ year old sprinklers, respectively. This difference was significant only between the new and oldest sprinklers. Leaching and applied water was always greatest near sprinklers when nozzles and spoons were more than two years old.

Table 1. Typical irrigation set times, sprinkler and root yield distribution uniformity (DU) characteristics of intensively sampled grids under varying sprinkler lateral spacings.

Lateral Spacing (ft)	Typical Irrigation Set Time (hrs)	Applied Water per Set (in)	¹ Total Irrigation for Season (in)	Mean Root Yield for Grided Plots (ton/ac)	² Mean Normalized Sprinkler DU (%)	Yield DU (%)	³ R ² for Normalized Sprinkler and Yield DU	⁴ Mean Evaluation DU (%)
SPRING 1996								
33.3	8.5	2.21	25.65	35.95	84.1	84.3	0.047	*80.6ab
40.0	10	2.16	25.63	37.35	81.6	81.5	0.114	78.1a
46.7	12	2.23	26.08	36.03	89.9	85.4	0.073	86.0 b
SPRING 1997								
42.0	10	2.41	30.94	*38.80a	87.6	89.3	0.054	82.0
48.0	12	†2.64	34.32	32.48 b	84.2	85.2	0.042	76.2
FALL 1997								
36.0	9.5	†2.67	19.64	35.91	84.2	87.2	0.063	75.2
42.0	11	2.35	17.96	34.58	90.8	85.6	0.124	77.4
45.0	12	2.40	17.27	34.81	87.6	88.0	0.054	71.8

¹ Rainfall negligible for fall 1996 and spring 1997. Fall 1997 includes 5.19" rainfall.

² Normalized precipitation for each grid element was computed as a percent of the average for each evaluation. The mean normal val for each element of all sprinkler evaluations times total precipitation for the season is used to compute mean normalized sprinkler D

³ R² values are for a second order polynomial regression of yield and normalized precipitation by grid element and spacing.

⁴ Equals the mean of computed DU values from individual evaluations. Does not include rainfall events.

*Numbers with different letters are significantly different at the 0.05 level.

† Pressure excessive due to cooperatior error when changing sets.

A "mean normalized sprinkler DU" was calculated to estimate the uniformity of precipitation for the whole season. This value accounts for shifts in wind pattern from one sprinkler evaluation to another and provides a more "plant based" viewpoint of seasonal precipitation uniformity. The result is a general increase of 4 to 8% in seasonal DU over the straight mean DU. These DU's (from a low of 81.6 to a high of 90.8%) are more consistent with the uniformity of total root yield as discussed below (Figs. 2 through 5). Natural rainfall greatly increased the seasonal uniformity of the fall 1997 trial (Table 1) despite the older sprinklers.

Total carrot root yield and quality was not statistically different for any of the spacings for sampling over the entire field, although a consistent trend of 2 to 6% increased yield for the closest spacing was observed for each trial (Table 2). Total root yield for the 42' foot intensively

Table 2. Total yield, growth rate and packout for 1996 and 1997 spacings.

Spacing (ft)	Total (ton/ac)	Marketable (ton/ac)	Plant Growth Rate ¹ (g/plant/day)	Root Growth Rate (g/plant/day)	Cello Pack Carrot Yield (ton/ac)	Baby Cut/Peeled Carrot Yield (ton/ac)	Cull (ton/ac)
Spring 1996							
33.3	42.6	41.2	0.077a ²	0.052a	15.5	25.7	1.6
40.0	40.9	39.9	0.063 b	0.042 b	15.3	24.2	1.1
46.7	40.4	38.8	0.069ab	0.047ab	14.4	24.5	1.6
Fall 1997							
36	36.3	33.0	0.067 b	0.053 b	27.5	5.6	0.6
42	34.4	30.1	0.066 b	0.050 b	25.3	4.8	1.5
45	34.3	31.2	0.081a	0.065a	25.1	6.2	0.5

¹ Average over the entire growing season.

² Values separated by different letters are significantly different at 0.05 confidence level.

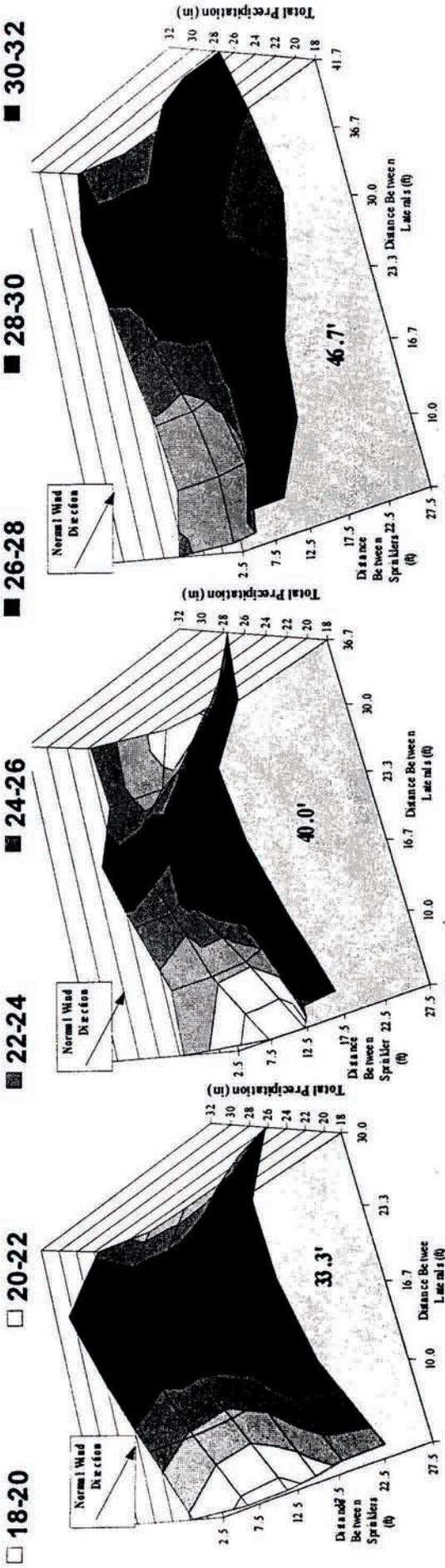


Figure 2. Surface plot of applied water for the entire season for all lateral spacings for Feb 1996 planting. Total applied water for each 5' by 6.7' (2 beds) grid element determined by normalized applied water from 5 to 7 sprinkler evaluations. Effective rainfall for season nil.

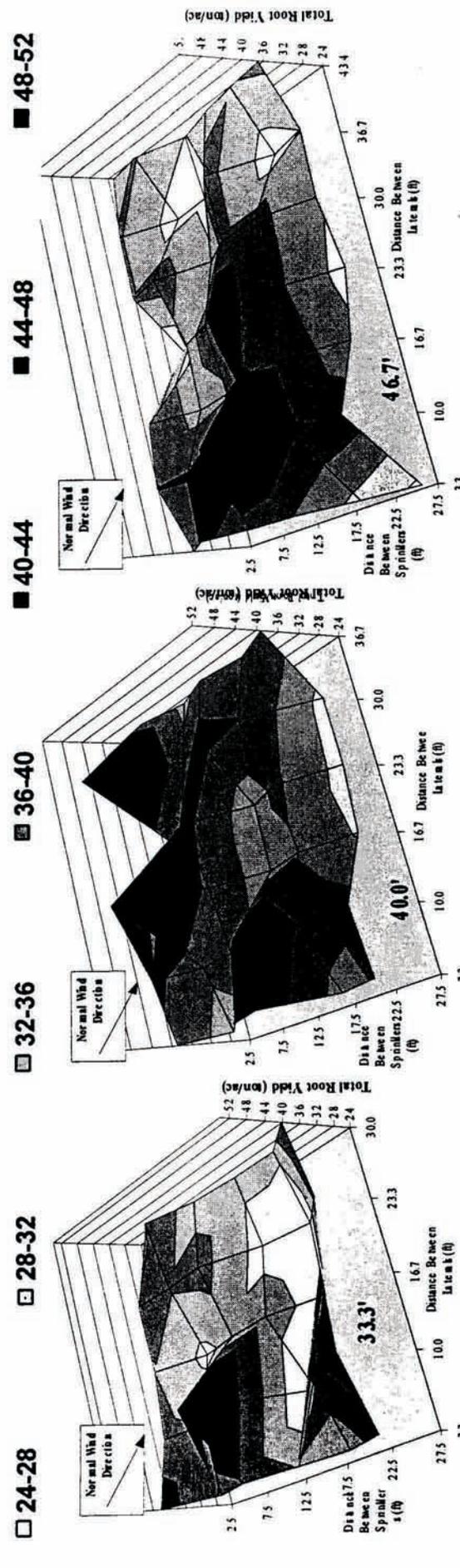


Figure 3. Surface plot of total root yield from intensively sampled grids corresponding to mean applied water shown in Fig. 2 for Feb 1996 planting.

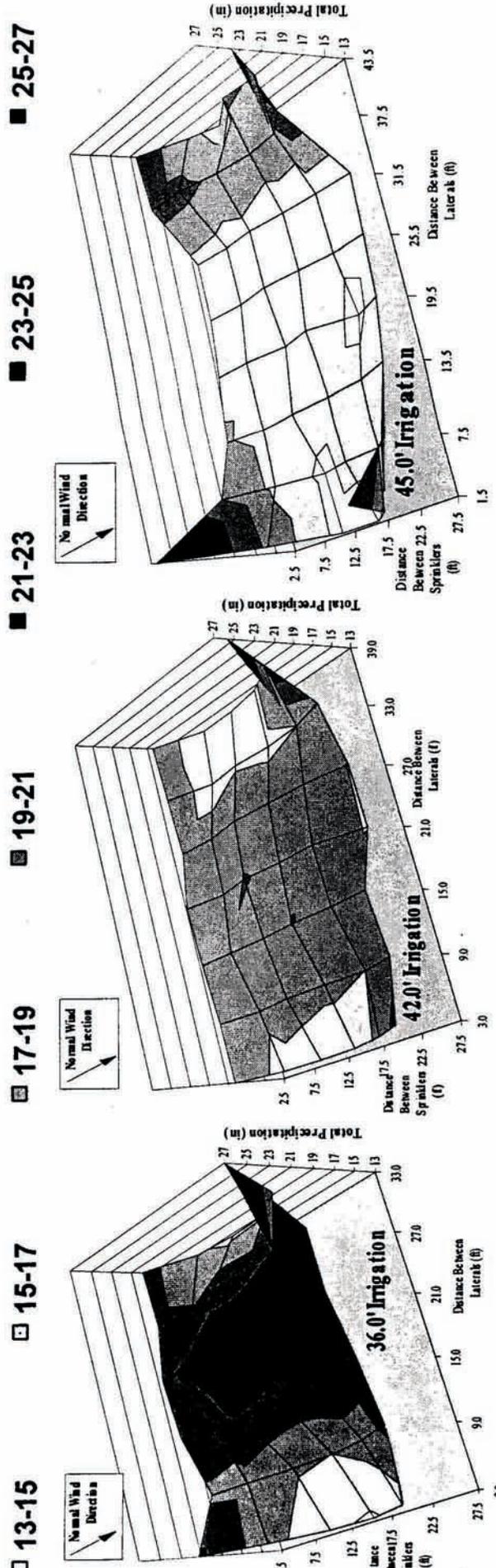


Figure 4. Surface plot of applied water for the entire season for all lateral spacings for Fall 1997 planting. Total applied water for each 5' by 6' (2 beds) grid element determined by normalized applied water from 5 to 7 sprinkler evaluations. Precipitation includes 5.19 inches of rainfall.

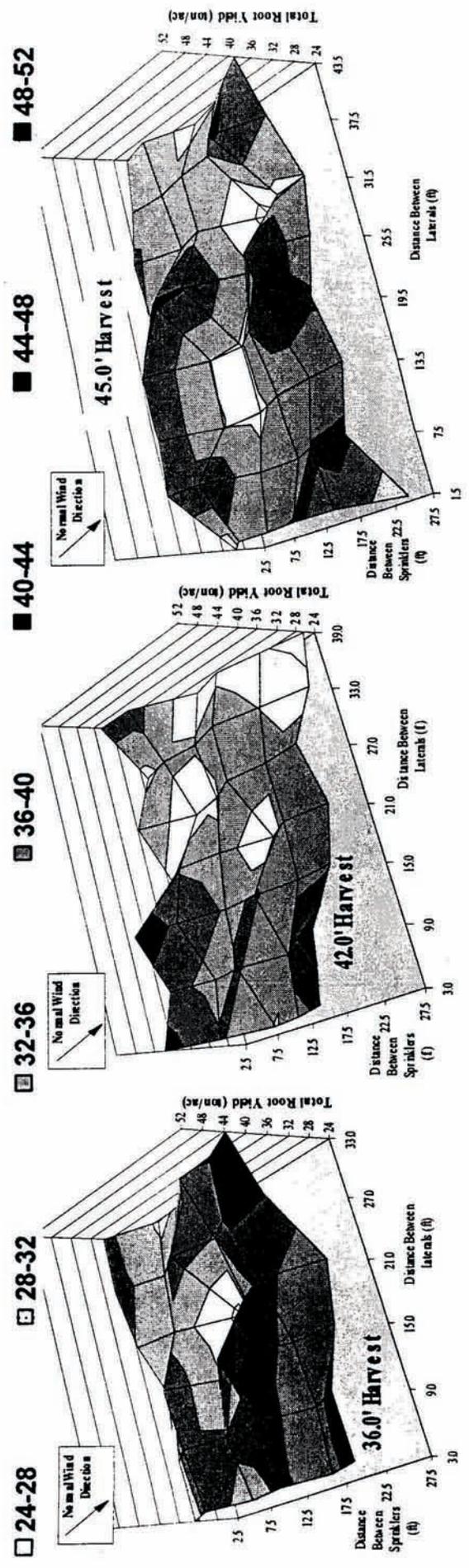


Figure 5. Surface plot of total root yield from intensively sampled grids corresponding to mean applied water shown in Fig.5 for Fall 1997 planting.

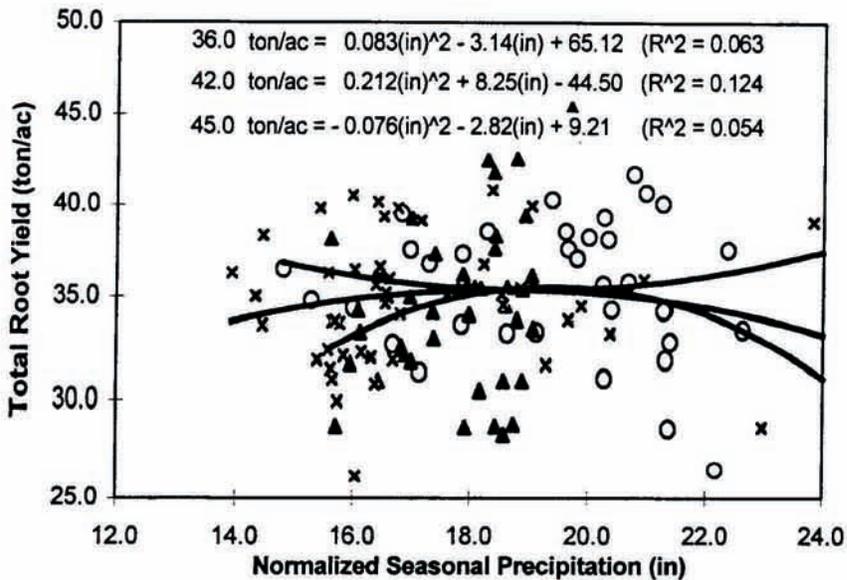


Figure 6. Second order polynomial regression of total root yield and normalized seasonal applied water for intensively monitored grids for all spacings for the fall 1997 trial. Same field and approximately same sites as spring 1996. trial.

monitored grid in the Spring 1997 trial was significantly greater than the grid from the 48' spacing by 6.2 ton/ac (Table 1), but this difference was reduced to 1.5 ton/ac for overall replicated field sampling. Total root yield DU ranged from 81.5 to 89.3% with no significant differences from lateral spacing. Total precipitation in monitored grids ranged from 75 to 160% of ET for the season depending on location relative to sprinklers. There was no correlation with yield and applied

water at these levels (Figure 6) for any spacing, suggesting that carrots are capable of maximum yield even under some deficit irrigation. Table 3, below, confirms these results for the replicated monitoring sites. No significant differences were found in yield or quality even though cumulative precipitation was significantly different for these locations.

Nitrate leaching as estimated by anion-exchange resin bags was found to be 7 to 12% (19.2 to 30.5 lb/ac) of applied N (250 lb/ac) in the Spring 1996 trial (Table 3). The 40.0' lateral spacing leached significantly less nitrate than the 33.3' or 46.7' spacings even though the 46.7' spacing

Table 3. Precipitation, nitrate leaching, plant growth, yield and quality as a function of monitoring location between sprinkler laterals for the same field over two different seasons.

Location	Total Precipitation (inches)	Resin Bag NO ₃ -N (lb/ac)	Plant Growth Rate ¹ (g plant/day)	Total Yield (ton/ac)	Marketable Yield (ton/ac)	Cello Pack Carrot Yield (ton/ac)	"Baby" Peeled Carrot Yield (ton/ac)	Cull (ton/ac)
Spring 1996								
Mid Sprink	22.8 a ²	19.6	0.072	42.0	41.1	14.2	26.4	1.0
Middle	23.2 a	21.1	0.065	40.8	39.0	16.3	22.7	1.8
Lateral	19.2 b	19.7	0.073	41.3	39.9	15.2	24.7	1.5
Fall 1997								
Mid Sprink	16.0 b	216.9	0.075	37.6	33.7	21.0	6.7	0.5
Middle	16.6 b	243.4	0.066	34.7	30.5	25.8	4.7	0.8
Lateral	14.2 c	255.4	0.075	32.4	30.3	25.4	5.0	0.6
Sprinkler	21.6 a	186.3	0.076	31.4	31.4	25.7	5.8	1.1

¹ Average over the entire growing season.

² Values separated by different letters are significantly different at 0.05 confidence level.

proved to have the highest mean DU. An 85% efficiency of nitrate recovery was observed for these bags using soil columns prepared in the laboratory from soils used in these trials. Use of these resin bags to accumulate total leached nitrate seemed highly promising after the first season. Intercepted nitrate in the spring 1997 trial jumped to 18 to 27% of applied N. Resin bag results from the Fall 1997 trials, however, showed impossibly high levels of nitrate leaching from 66 to 132% (more than 300 lb/ac for the 36' lateral spacing) of applied nitrogen. (Leaching data by spacing is reported in the 1998 Fertilizer Research and Education Program proceedings).

Examining the degree of leaching by 'Location Relative to Sprinklers' (Table 3) reveals a much greater differential than seen between different lateral spacings. Data reported in Table 3 excludes the Spring 1997 trial (see FREP 1998 Summary), concentrating instead on the two carrot plantings from the same field and nearly the same sampling locations over two different seasons.

NO₃-N concentrations in soil solution access tubes (SSAT) were also unrealistically high. Further confounding these results is the fact that intercepted resin bag nitrate was lowest for the Sprinkler location that had the greatest precipitation and should have realized the greatest flux of nitrate over the season. This location should have yielded the highest amount of intercepted nitrate as most of the fertilizer was injected into the irrigation water (100 lb/ac preplant broadcast with a terrigator and 150 lb/ac N as 10-0-12 and UN32 through fertigation). Appropriate lab procedures appear to have been followed and control bags showed zero nitrate contamination. After seeing elevated levels of nitrate leaching in the Spring 1997 trial we had some concerns about passive diffusion of soil nitrate into the resin bags that represents part of the background soil N pool that is not necessarily being leached out of the profile. A few bags were installed in the Fall 1997 trial that were exposed to the soil at the 3' depth, but protected from any leaching of water from above. These bags showed 30 to 50 ppm accumulated NO₃-N, which translates to 35 to 65 lb/ac NO₃-N that did not actually "leach" through these bags but was absorbed from nitrate resident at that depth. Values of leached nitrate reported in Table 2 has not been discounted by these amounts as the "diffusion bags" were placed at four locations only. An average "diffusion value discount" would have caused some monitoring sites to have negative nitrate leaching. More benchtop studies using these resin bags are needed to resolve this issue.

Nitrate leaching estimates from site-specific soil sampling is confounded by soil heterogeneity. Figure 7 illustrates the variability of the 1996 seasonal mean soil nitrate concentrations for all the spacings at the 1, 2, 3, and 4-foot depths.

The 1 to 2 foot depth had the greatest concentration of clay relative to the other depths, and, therefore showed the highest concentration of nitrate. However, there was no correlation with soil nitrate at this depth and nitrate leaching as estimated by resin bags (Figure 8). Instead, cumulative leaching appeared significantly related to soil nitrate at the 3 to 4 foot depth. Even though this relation-ship is highly significant (a 99.9% confidence), **the margin of error means that net nitrate leaching could be anywhere from ten to twenty times the soil nitrate concentration in these sandy soils.**

The NO₃-N distribution from the intensive sampling grids of 1996 showed nonuniform and random distribution. The semi-variograms showed a random NO₃-N distribution at 0-1' depth for 40' spacing, and at the 1-2' depth and 3-4' depth for both 33.3' and 46' spacings. Although the

variograms for the other depths and spacings indicate a Gaussian structure for NO₃-N distribution this pattern was not clearly reflected in soil nitrate contour plots (Fig. 7) and were not of significant impact in computer simulations. Soil NH₄-N contents measured with the intensive sampling grids were all randomly distributed.

Figure 10 shows a significant relationship between declining soil nitrate levels with increasing deep percolation for the 1 to 2 foot depth (the zone of slightly higher clay content). Leaching ran 0 to 6 inches depending on location for 1996 and 2 to 12 inches for 1997. Thus, cumulative nitrate leaching for 1997 would have been substantially higher than 1996 with the end result being uniformly lower soil nitrate levels.

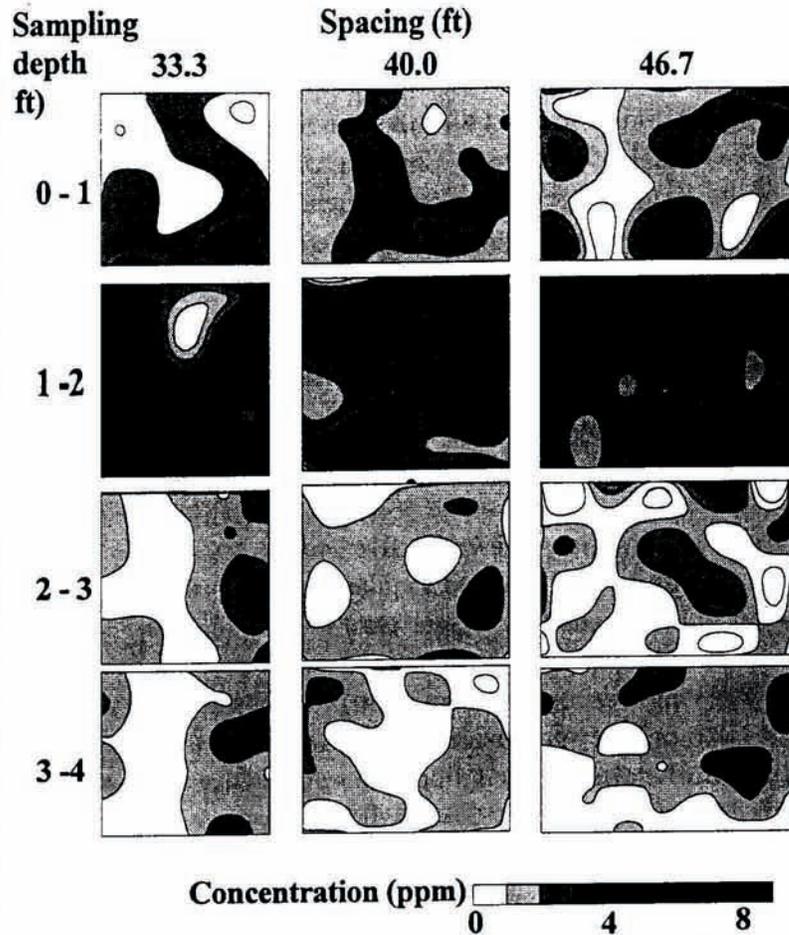


Figure 7. Seasonal (1996) average soil nitrate distribution at depths and for different sprinkler spacings.

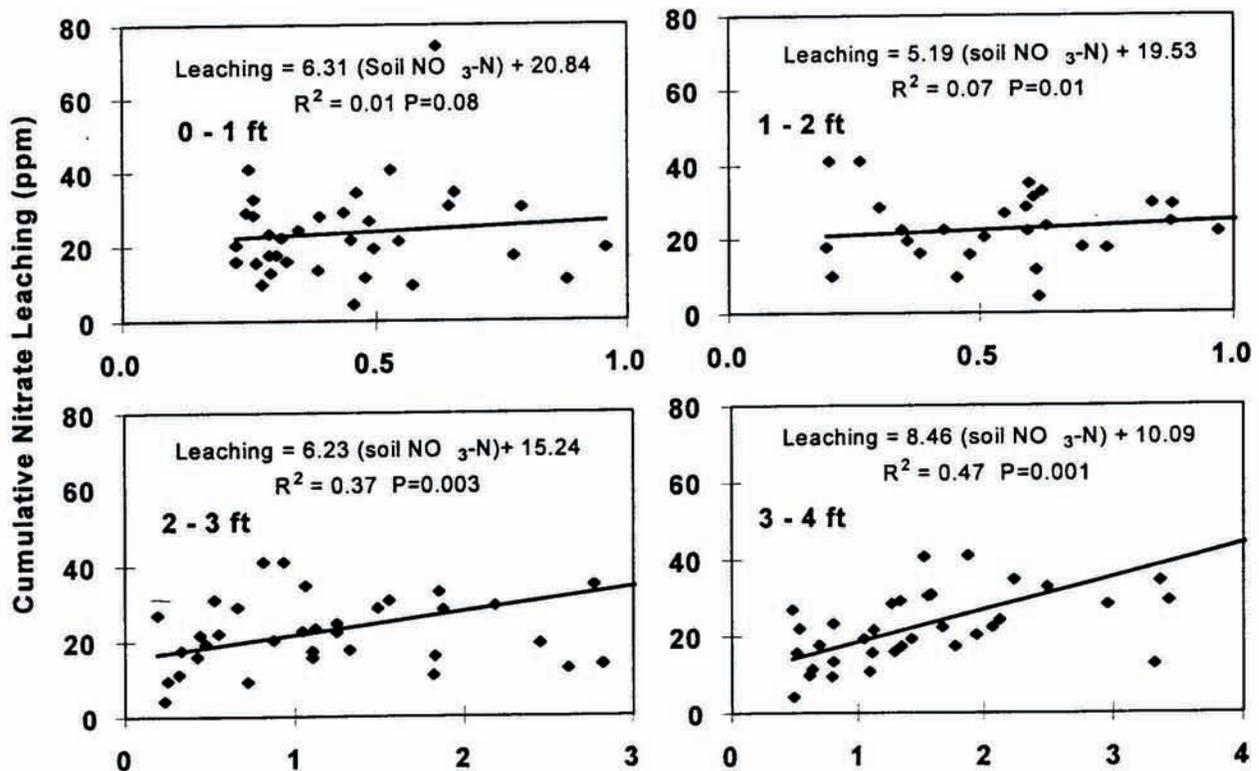


Figure 8. Relationship of cumulative nitrate leaching (as determined by resin bags) and soil nitrate at various depths for all sampling locations for the 1996 carrot crop.

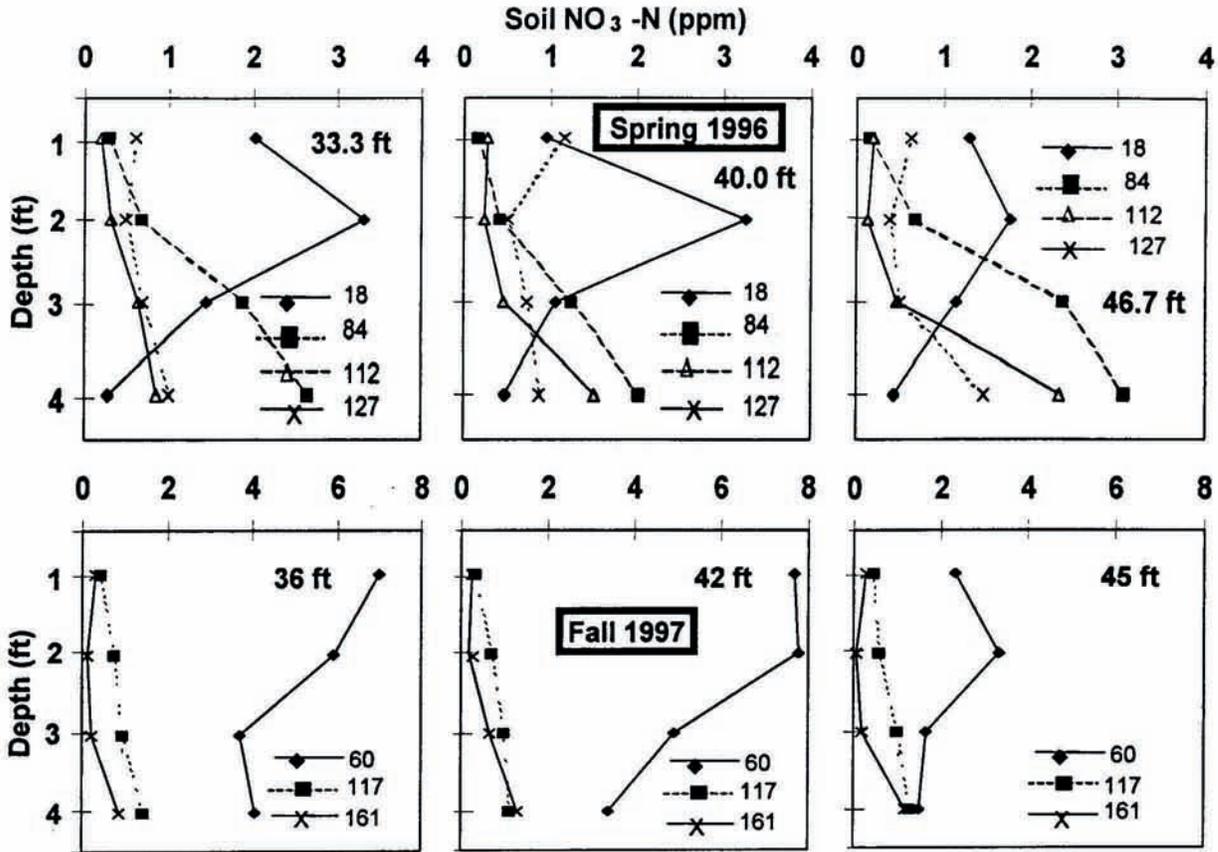


Figure 9. Change in soil nitrate with depth during the season. Legend indicates days after planting when sampling was done.

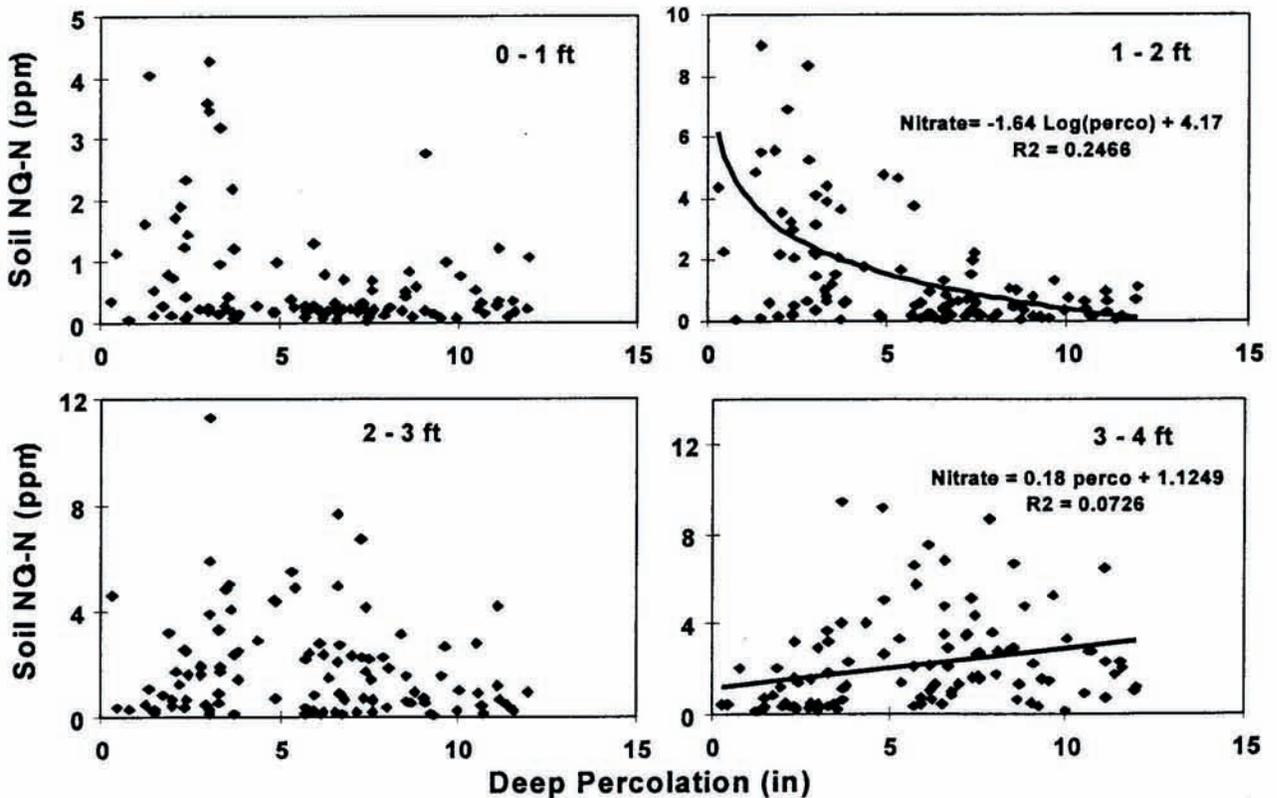


Figure 10. Soil NO₃-N concentrations as a function of cumulative deep percolation at that sampling location at the time of sampling. Deep percolation was estimated by subtracting crop ET as determined for the whole field from cumulative precipitation applied to that sampling location. Data for 1996 and 1997 crops are combined.

On average, nitrate content was 0.97 ppm in Spring 1996, which was significantly lower than 3.09 ppm in Fall 1997. The higher values in Fall 1997 were associated with fertilizer input for potatoes planted in the spring prior to carrots. Figure 9 reveals that for the Fall 1997 crop, total soil nitrate load in the top four feet at 60 days after planting (about 11/1) was two to three times greater than 18 days after planting for the Spring 1996 crop. However, at the end of the season more soil nitrate was present at the 4-foot depth for the 1996 crop than the 1997 crop. This is not surprising as more than twice the leaching occurred during the 1997 planting due to the late summer irrigations required for germination and winter El Nino rains.

Task 2: Adapt an existing computer model to assess water and N fertilizer management under various sprinkler lateral spacings.

Model description

Our field experiment showed that the three lateral spacings of the sprinkler irrigation system did not show significant difference with respect to irrigation uniformity. However, evaluation of various DU on carrot production and nitrogen uptake and leaching is important to maximize N uptake and reduce nitrate leaching. The simulation conducted in this study used the ENVIRO-GRO model developed by Pang and Letey (1998). The model has the capability to simulate (1) water, salts, and nitrogen movement in the soil with plant growth; (2) plant response to soil water, salinity, and nitrogen stress; (3) drainage and salts and N leaching; and (4) cumulatively relative transpiration and relative N uptake, and consequently relative crop yield. In this study, the ENVIRO-GRO model was adapted to simulate carrot growth in three soils with different textures and to assess the irrigation uniformity impact on carrot growth, ET, percolation loss, N uptake, and nitrate leaching.

Monte Carlo simulation

A DU value is a relative measure of irrigation water distribution on the soil surface. A single DU value does not provide sufficient information for the model to simulate the irrigation uniformity effect on carrot growth and N partition in plant and soil. In this study, a Monte Carlo method was used to generate 100 irrigation depths for each soil. The number generator was based on the field measured irrigation depth distribution from the catch-can method (the generated and catch-can measured numbers have the same distribution and variation). The generated numbers represent irrigation depths measured by 100 catch cans, and each depth was used to run the model for the whole growing season. Four DU numbers of 50, 75, 90, and 100% along with their variances were used. The output from each run (100 runs for each of the three soil types) was then used to calculate the average ET, percolation, N uptake, nitrate leaching, and relative yield.

Other Input data

Soil hydraulic properties of the sandy loam was from Pang and Letey (1998). The silty clay loam was from the lab experiment of Leung (1998, Ph.D. thesis), and the sandy soil was from soil survey data of Kern County, CA (Soil Conservation Service). The characteristics of the three soils are listed below.

The simulation used the same amount of N fertilizer as was applied in the field for spring 1996. The N application methods were the same as for spring 1996. The ET rate in the simulation was adjusted to get the same seasonal total ET of 80 cm. The root growth (depth and shape) was adjusted to get the same N uptake, and it was within the normal growth range.

Results

Relative yield and seasonal ET was substantially affected by changes in DU in coarse textured soils, but has little or no effect on carrots growth in a fine soil. In the sand and sandy loam, relative yield of carrots increases as irrigation uniformity increases. In the silty clay loam, however, the relative yield was not affected by irrigation uniformity. The simulation also showed that carrot yield is relatively lower in a fine-textured soil than in a coarse-textured soil. The seasonal ET has the same trend as the relative yield, i.e., ET increases as the uniformity increases for the sand and the sandy loam; but ET was not affected by uniformity in the silty clay loam. Like the relative yield, total seasonal ET in the silty clay loam was much less than in the sand and sandy loam,

Nitrogen uptake in the sand and sandy loam increases as the irrigation uniformity increases; while N uptake was barely influenced by irrigation uniformity in the silty clay loam. This is consistent with the simulated relative yields. A higher yield in a field receives more uniform irrigation results in higher N uptake in the coarse soils, while nearly the same relative yield results in similar N uptake under different irrigation uniformities in the silty clay loam.

Nitrate leaching decreases dramatically as the irrigation uniformity increases in the sand and sandy loam. Two factors contributed to the decrease in nitrate leaching in a field receives high uniformity irrigation: (1) as the ET increases, the amount of water percolation to deep soil decrease; and (2) as ET and carrot yield increases, N uptake by carrots increases. In the silty clay loam, nitrate leaching was not affected by uniformity, but the leaching is lower than the coarse soils due to decreased losses to deep-percolation. The model did not simulate the surface runoff. The runoff water will also carry away the N in the irrigation water.

In summary, the model is capable to simulate the growth of carrot and other shallow-rooted crops and irrigation uniformity effect on nitrogen uptake and nitrate leaching in soil. The simulated results showed that the sand soil has the highest, and the silty clay loam has lowest carrot yield. The yield increases as the uniformity increases in coarse-textured soils. Nitrogen uptake is positively correlated to the total seasonal ET and crop yield, thus N uptake increase as uniformity increase in the coarse-textured soils. Irrigation uniformity has little effect on N uptake and leaching in the silty clay loam.

Plant data for the model simulation.

Item	Data
Carrot growth simulation period	130 days
Time when vegetative growth started	5 days
Time when crop cover fully developed	130 days
Time when crop was matured	130 days
Maximum root depth	(very thin from 60 cm) 1m
Time when crop reaches maximum root depth	130days
Crop coefficient during the growing season	0 to 1.1
ET ₀	Same as for spring 1996
Salt tolerance	Very high

Management data for model simulation.

Item	Data
Initial N amount in the soil profile	7.9 kg ha-1
Nitrogen incorporated before planting	135 kg ha-1
Total N application during season (Started from the 6th irrigation)	145 kg ha-1
Total seasonal irrigation depth (12 irrigations, once every other week)	75 cm
N mineralization	0
Salinity	0.2 dS/m

Boundary conditions.

Item	Data
Soil surface initial pressure	-10 cm
Soil at 5 m initial pressure	-10 cm
Surface boundary	ET and irrigation
Lower boundary	Zero pressure head gradient

Soil characteristics

Item	Sandy soil	Sandy loam	Silty clay loam
Ks (cm hr-1)	2	4	0.01
θ_s (cm ³ cm-3)	0.5	0.48	0.542
θ_r	0.05	0.05	0.229
θ_i	0.49	0.48	0.542
ϕ_i	-10	-28	-10
α	-10	-28	-10
β	3.5	3.8	8.4
ρ_b (g cm-3)	1.3	1.4	1.3

Saturated hydraulic conductivity (K_s) values for the field used in the Spring 1996 and Fall 1997 trials ranged from a high of 3.35 in/hr in the top foot of soil to 0.94 in/hr at the four foot depth, with coefficients of variation (CV) for these values of 31 to 120%, respectively. Nitrate leaching proved to be significantly correlated with K_s only at the four foot depth ($R^2_{\text{simulated}} = 0.863$ and $R^2_{\text{actual}} = 0.712$). Simulated values agreed very well with the actual data from this field. Our simulation model reveals that nonuniform leaching can still be significant in a spatially variable soil even though the irrigation DU is 100%.

Task 1 Addendum: Regional irrigation system evaluations to examine the impact of sprinkler age

Evaluations of grower fields across Kern County revealed that this factor was not significant in improving DU. Forty-two evaluations of solid-set systems in ten different fields throughout

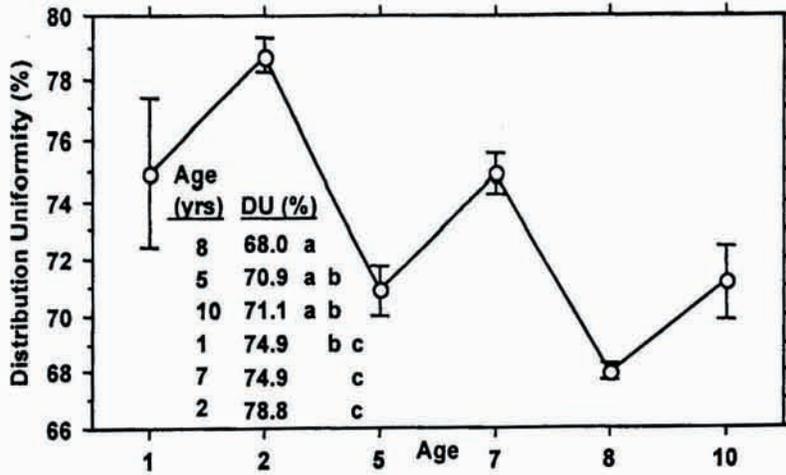


Figure 11. Impact of sprinkler system age on DU. Includes evaluations performed with new nozzles and sprinklers.

joins down from that (240 feet away from the first catchcan set. For the 12 sprinkler heads surrounding the location of the second catchcan set we installed new nozzles (either 7/64 or 1/8 inch depending on the grower's system) into the grower's old sprinklers. For the third set, 12 new sprinkler heads were installed. The old sprinkler, new nozzle and new sprinklers were of course run simultaneously so that wind conditions and duration would be identical for all three evaluations. Increasing system age showed a slight trend toward decreasing uniformity (Figure 11), but direct comparison of the original, new nozzles and new sprinklers showed no impact at all for age (Figure 12).

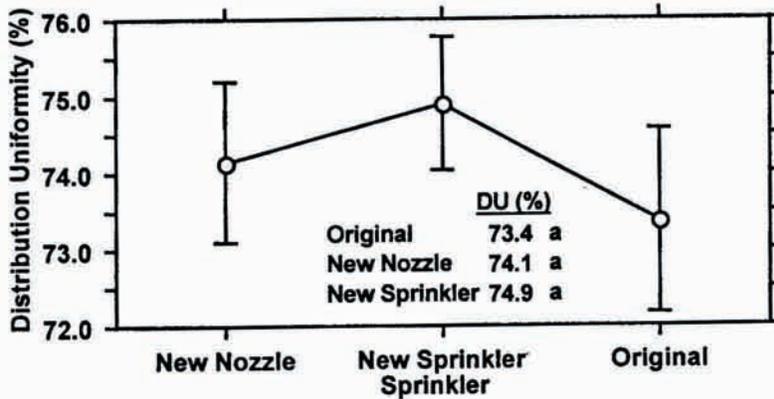


Figure 12. Impact of new nozzles and sprinkler heads on DU.

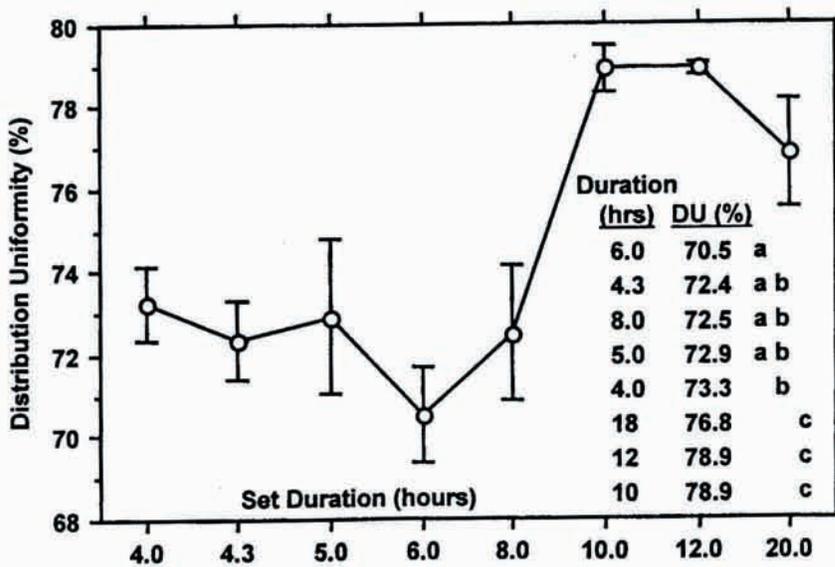


Figure 13. Impact of set duration and accumulated precipitation on DU

Kern County on irrigation systems ranging in age from 1 to 10 years were carried out between June 1998 and May 1999. Set duration ranged from 4 to 12 hours. The grower's existing system DU was evaluated in the same manner as for the carrot fields in the earlier part of this project. Using the same two laterals as those for the grower's system evaluation we installed a second set of catchcans four joints of pipe down the line (120 feet) and a third set another four joints down from that (240 feet away from the first catchcan set. For the 12 sprinkler heads surrounding the location of the second catchcan set we installed new nozzles (either 7/64 or 1/8 inch depending on the grower's system) into the grower's old sprinklers. For the third set, 12 new sprinkler heads were installed. The old sprinkler, new nozzle and new sprinklers were of course run simultaneously so that wind conditions and duration would be identical for all three evaluations. Increasing system age showed a slight trend toward decreasing uniformity (Figure 11), but direct comparison of the original, new nozzles and new sprinklers showed no impact at all for age (Figure 12).

Set duration, or cumulative precipitation, made the most significant impact on DU (Figure 13). A very clear breakpoint at 10 hours was evident. Below this duration DU averaged around 72%. At or above this threshold the average was about 78%. This analysis includes three evaluations of an 18-hour duration that was actually the total precipitation from four; 4.5-hour

irrigation sets in potatoes. As shown by the “seasonal normalized precipitation” DU from the carrot trials, variability in wind patterns increases DU over multiple sets.

Figure 14 illustrates the depth of precipitation and corresponding DU for 5, 10, and 18 hour irrigation durations for the original grower sprinklers for 7 year old solid-set sprinkler pipe in potatoes with a 45 foot lateral spacing and 7/64 nozzles. The one disadvantage of older sprinklers is increased misting from worn nozzles and spoons. Even though this figure shows the typical spike in the amount of precipitation within 3 to 5 feet of the sprinkler, this does not represent a major decrease in DU.

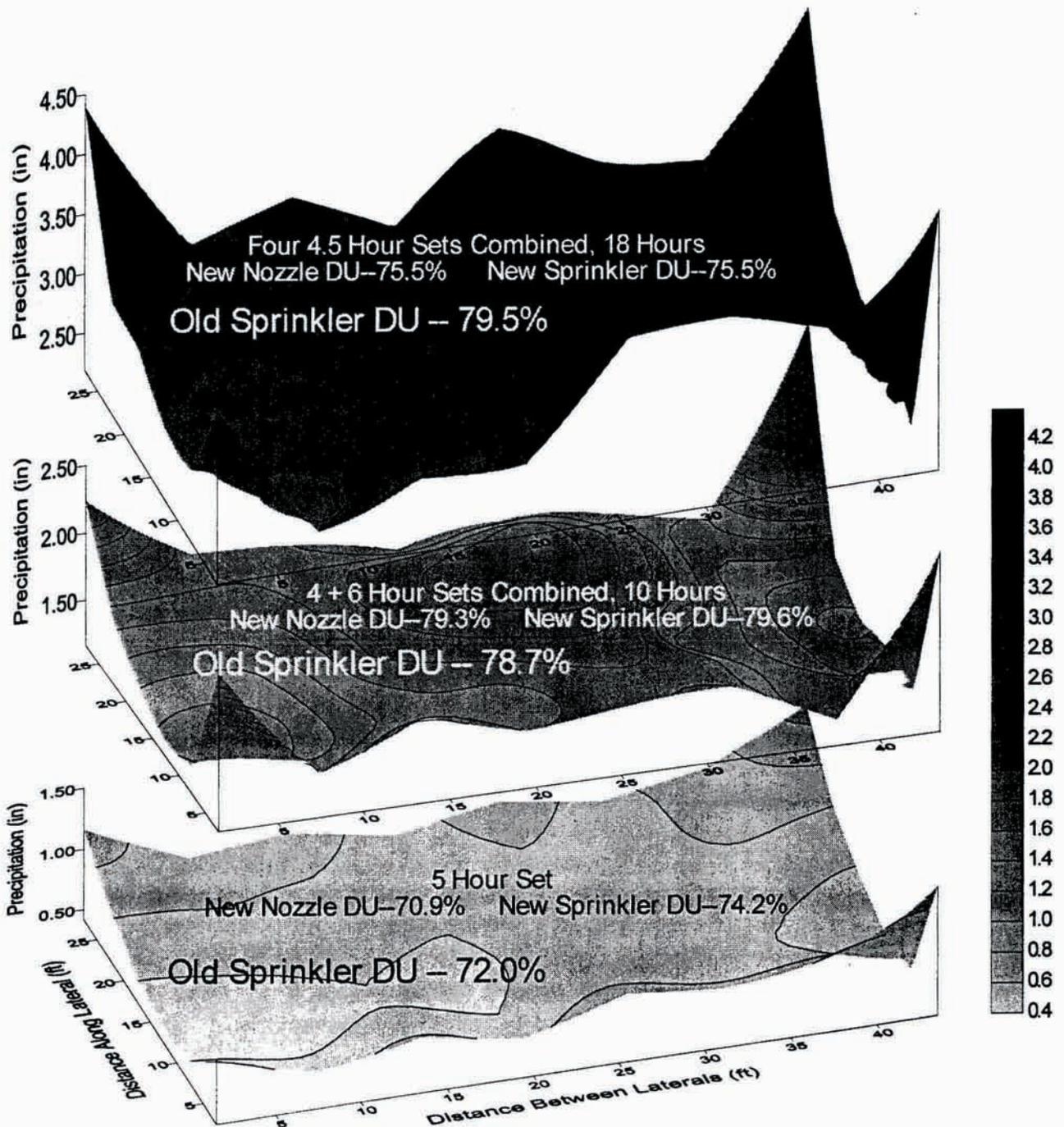
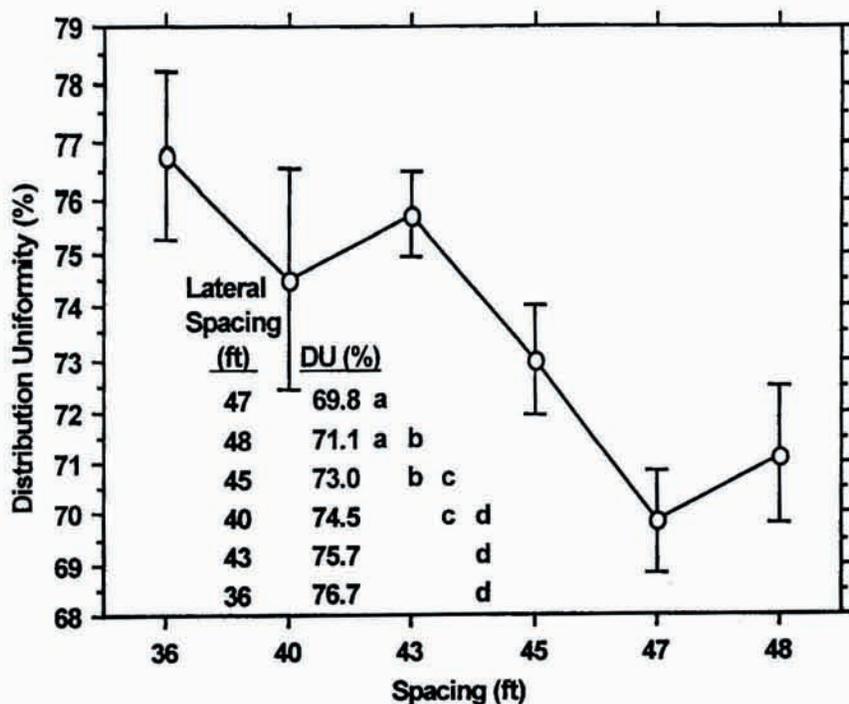


Figure 14. Surface contours of sprinkler precipitation for irrigation durations of 5, 10 and 18 hours using seven-year-old Weather-Tec 10/20 sprinklers on two-foot risers with 7/64 nozzles running at 52 psi.

Finally, despite the results of 44 separate evaluations of the seven different lateral spacings



examined during the carrot trials, narrower lateral spacing in these regional evaluations gave significantly higher DU than the 45 to 48 foot spacings (Figure 15). This does concur with our computer modeling simulations in which DU improved with narrower spacing. However, our earlier fieldwork in this project indicates that this benefit may disappear when considering precipitation uniformity over the whole season, and probably not translate into any yield benefit.

Figure 15. Impact of lateral spacing on DU for one-time regional tests.

Conclusions

This study showed that sprinkler spacing and precipitation uniformity has much less effect on nitrate movement than suggested by earlier studies. Under conditions similar to our study (seasonal irrigation uniformity >75% with the crop receiving sufficient water and fertilizer) sprinkler lateral spacings from 33 to 47 feet would not differentially impact yield, nitrogen distribution/use or nitrate leaching.

Nitrate leaching in Kern County carrot fields with sandy soils appears to range from 15 to perhaps more than 60 lb/ac N depending on previous crop rotation and time of planting. Current resin bag methodology proved undependable for verifying total nitrate leaching in the second and third test fields. The reasons for this are unclear at this time but appear to be related to the adsorption of existing soil nitrates at the time of installation and perhaps the length of time bags remain in the soil. Resin bag estimates of nitrate leaching were only weakly correlated to deep percolation, were not at all correlated to lateral spacing, but were significantly related to soil nitrate concentrations at the three and four foot depths in 1996. Soil nitrate levels were significantly related to deep percolation at the three-foot depth where clay content was slightly higher. Soil nitrogen reserve in the form of ammonium content and distribution for both years was not correlated to lateral spacing or irrigation uniformity. Our computer simulations and field data indicate that there is a threshold DU (possibly around 75%) and minimal clay content above which yield and nitrate leaching will be unresponsive. At this point, assuming proper scheduling of irrigations and fertilizer application, the natural variability of soil characteristics determines the extent of deep percolation and nitrate leaching.

Regional sampling of 1 to 10 year old solid-set sprinkler systems across Kern County showed that DU was not significantly affected by the age of nozzles and sprinkler heads.

Specifically, this project found that:

- **Single event irrigation evaluations** for field distribution uniformity of sprinkler precipitation can **underestimate season-long irrigation uniformity by 5 to 15%**.
- **Carrot yield was unaffected** as long as applied water was between **75 to 160% of ET**.
- **Computer modeling and field data** indicate that there is probably a **threshold DU** (perhaps 75%) and minimal clay content, above which yield, water and nitrogen use efficiency will not be improved.
- **Nitrate leaching** appears to be between 10 to 25% of applied N in Kern County carrot production, but current resin bag and SSAT technologies do not provide an accurate estimate.
- **Sprinkler age** for a given spacing does not significantly impact DU, but narrower lateral spacing and longer set duration (10 hours or greater) significantly improve DU as measured by a “one-shot” catchcan evaluation. This is probably less significant over the whole season.

Recommendations

- **For low to moderate wind conditions**, lateral spacings of 33 to 47 feet using 7/64 nozzles will achieve optimal yields where set duration is 8 to 14 hours. Use narrower spacing for higher wind or short set (less than 6 hours) conditions.
- **Nozzle size and set duration** must be appropriate for your soil water holding capacity and crop rootzone storage. The average applied irrigation depths should be only 5 to 10% above estimated crop ET. Shallower rooted crops require shorter set durations to minimize leaching. A 2” application is great for carrots but probably too much for garlic and onions.
- **Maintain nozzle pressure** (for straight bore nozzles) @ 52 to 57 psi for the best pattern. Check it with a gauge! Replace worn pipe gaskets at least every 3 years and sprinkler head gaskets every 5 years. You can lose 10% of your water through these leaks.
- **Fertilizer injection through the sprinklers (fertigation)** should only be carried out to match periods of peak crop demand and applied toward the latter half of the irrigation set duration to minimize leaching.

Task 3: OUTREACH ACTIVITIES

Publications:

Allaire-Leung, S., L. Wu, J. Mitchell, B. Sanden. 1999 (submitted). Sprinkler spacing and irrigation uniformity effects on soil nitrate content and leaching. *J. Ag. Water Management*.

Mitchell, J., B. Sanden, L. Wu. 1996, 1997, 1998, 1999. Effects of irrigation nonuniformity on nitrogen and water use efficiencies in shallow-rooted vegetable cropping systems. Fertilizer Research and Education Program Conference Proceedings, CDFA Sacramento, CA.

Mitchell, J.P., S. Allaire-Leung, B.L. Sanden, L. Wu. 1999 (accepted). Sprinkler spacing effects on carrot yield and quality. *J. Hort. Sci.*

Sanden, B. 1998. Narrow sprinkler spacing not always best. News Release, 11/6.

Sanden, B. Irrigation uniformity and water use efficiency in Kern County. 1999. Written testimony for CALFED public meeting, 9/14 Visalia, CA. Also News Release.

Sanden, B., J. Mitchell, L. Wu, S. Leung. 1999. Irrigation uniformity, nitrate leaching and yield distribution of carrots under alternative sprinkler spacings. Proceedings for UC Seminar: Advances in Irrigation. Kearney Ag Center, Visalia, CA, 11/17.

Sanden, B., J. Mitchell, L. Wu, S. Leung. 1999. Irrigation uniformity, nitrate leaching and yield distribution of carrots under alternative sprinkler spacings. Proceedings for Pacific Northwest Vegetable Association Annual Convention and Tradeshow: Harvest the Future. Pasco, WA, 11/18-19/99.

Sanden, B.L., J.P. Mitchell, L. Wu, S. Allaire-Leung. 2000 (abstract accepted). Impact of sprinkler lateral spacing on field distribution uniformity of precipitation and carrot yield. Proc. 4th Decennial National Irrigation Symposium, Phoenix, AZ, Amer. Soc. of Ag. Eng.

Posters:

Effects of irrigation nonuniformity on nitrogen and water use efficiencies in shallow-rooted vegetable cropping systems. 94th Annual Conference of the American Society of Horticultural Science. Salt Lake City, UT, 7/23-26/1997.

Effects of sprinkler spacing on irrigation uniformity, nitrogen leaching and yield in carrots. 1999 Plant & Soil Conference: Ag Technology—Moving California into the 21st Century. Visalia, CA 1/20-21/99. Also presented at the Annual Cotton Field Day, Shafter Research and Extension Center, 9/21/99.

Presentations:

Fifth Annual Fertilizer Research and Education Program Conference. Sacramento, CA, 11/18/97.

Sprinkler spacing, nitrogen and water use efficiency in carrots. Vegetable Crops Conference, South San Joaquin Valley. Visalia, CA, 1/29/98.

Irrigation Management of Carrots. Kern County Carrot Production Meeting, 5/28/98

Sixth Annual Fertilizer Research and Education Program Conference. Fresno, CA, 11/17/98.

Sprinkler Irrigation Management. Kern County Potato Production Meeting, 12/16/98.

Irrigation uniformity, nitrate leaching and yield distribution of carrots under alternative sprinkler spacings. UC Seminar: Advances in Irrigation. Kearney Ag Center, 11/17/99.

Irrigation uniformity, nitrate leaching and yield distribution of carrots under alternative sprinkler spacings. Pacific Northwest Vegetable Association Annual Convention and Tradeshow: Harvest the Future. Pasco, WA, 11/18-19/99.

Impact of sprinkler lateral spacing on field distribution uniformity of precipitation and carrot yield. 4th Decennial National Irrigation Symposium, Amer. Soc. of Ag. Eng. Phoenix, AZ, 11/14-16/2000

Additional Venues:

Occasional radio spots on Kern County UCCE daily radio tapes. Currently aired on 4 stations.

Brief discussion of lateral spacing based on this work, Buttonwillow Irrigator's Workshop sponsored by Natural Resources Conservation Service, 2/6/98.

Used data in panel discussion, Agricultural Water Use Efficiency: What's the Beef and Where is it Anyway, at California Water Policy Conference IX: Integration or Disintegration?, 10/14-15/99.

References

Pang, X.P., and J. Letey. 1998. Development and evaluation of ENVIRO-GRO, an integrated water, salinity, and nitrogen model. Soil Sci. Soc. Am. J. 62:1418-1427.